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Phenomenon Observation of Selective Withdrawal of bottom density currents through a Line Sink

Chien-Jung Liu¹, Shaohua Marko Hsu², and Wei-Sheng Yu³

ABSTRACT

A rectangular flume of dimension 180cm long \times 40cm high \times 5cm wide was used to observe the flow condition of density current withdrew by a line sink. Saline water is used as dense fluid to form a bottom density current. Red color is applied for dyeing dense fluid for observing the interface which is between lower-layer flow and upper-layer flow of the two-layer flow system. The vertical concentration profile of the density current, the entry angle which between the interface and the centerline of the slot, and the outflow concentration are measured after the equilibrium state is reached. The thicknesses of lower-layer flow with high concentration and entry angles were studied, which had been discussed via theoretical reasoning but not experimental data in selective withdrawal. The former has an asymptotic value as concentration over a critical value in each inflow discharge. The latter are close to theoretical values calculated by the equation of Forbes and Hocking (1998) especially when the entry angle is small.

Key word: two-layer flow; density current; selective withdrawal; link sink.

1. INTRODUCTION

In Taiwan, typhoons always bring a great deal of rainfall during June to October every year. The great quantity of water that falls on the drainage area will scour and bring much sediment particles flowing into the reservoir. The Coarser particles will deposit and form a delta near the headwater area. The muddy fluid that carries finer particles through the delta and moves further downstream called quasi-homogeneous flow (Yu et al., 2000). Because the high density of the muddy fluid, it will plunge down and form a bottom stratified current flowing to the downstream. Lee and Yu (1997)

¹ Ph.D. Candidate, Institute of Civil & Hydraulic Engineering, Feng Chia University, 100 Wen-Hua Rd, Taichung, Taiwan 407, R.O.C., p9112253@fcu.edu.tw

² Professor, Department of Water Resources Engineering, Feng Chia University, 100 Wen-Hua Rd, Taichung, Taiwan 407, R.O.C., shhsu@fcu.edu.tw

³ Assoc. Prof., Dept. of Finance, Chungyu Institute of Technology, Keelung, Taiwan 201, R.O.C

indicated that the quasi-homogeneous flow gradually becomes stratified and plunges into the bottom of the reservoir when the average densimetric Froude number for each section reaches 0.6 to 1.0. When the bottom stratified current arrive at the dam, it will form a muddy lake near the dam site (Fig. 1). The suspended finer sediment particles in the muddy lake will gradually deposit and consolidate into the bed. The deposition will decrease the storage capacity of the reservoir. It is relatively difficult to measure the bottom stratified currents and muddy lakes in a reservoir during typhoons because of the limitation imposed by nature. Therefore, numerical simulations are typically used to assess these aspects. Before one can use a model however, it is necessary to perform a calibration and validation step.

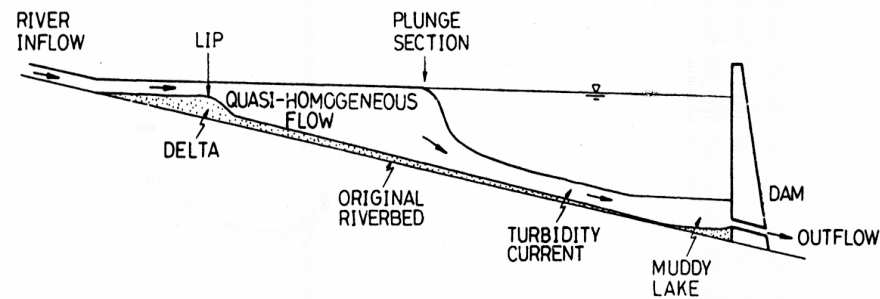
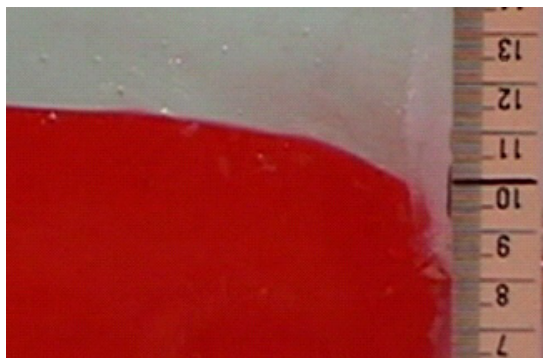
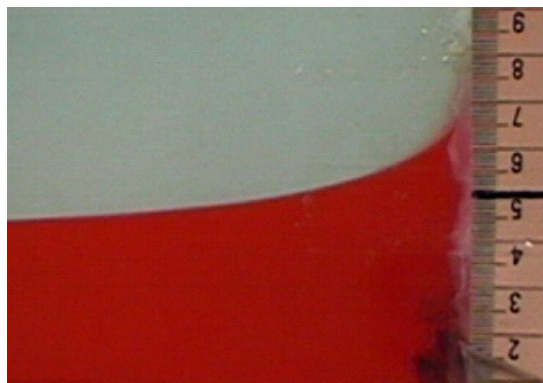


Fig. 1 Schematic diagram on the formation of a muddy lake in a reservoir

A large portion of previous research on selective withdrawal discusses the critical parameters for the beginning/ceasing of aspiration for a specific layer (Yu et al. 2004). Yu et al. (2004) discussed the thickness of lower-layer flow with variation of inflow discharge and concentration. The major results were as follows: in non-bottom-slot cases, the interface is drawn down (Fig. 2(a)) or sucked up (Fig. 2(b)) directly into the sink when the interface is above or below the slot elevation, respectively. In the former, the thickness is inversely proportional to the inflow concentration of the lower layer, and linearly proportional behavior exists in the latter due to a downstream effect of suction force by the slot opening.



(a) Drawdown curve near the slot



(b) suck-up curve near the slot

Fig. 2 Interface shape of drawdown curve and suck-up curve near the slot

Hocking and Forbes (2001) indicated that the theory of selective withdrawal in most previous studies was assumed that the flow condition is steady and irrotational, and the fluid is inviscid and incompressible, such as Craya (1949), Bear and Dagan (1964), Tuck and Vanden-Broeck (1984), Hocking (1991), Hocking (1995), Hocking and Forbes (2001). Forbes and Hocking (1998) analyzed the entry angle of the stratified flow from a pipe and the depth is finite. The angle, between interface and centerline of line sink, was calculated by the discharge ratio of lower-layer flow and total flux, and density ratio of dense flow and ambient water (Fig. 3).

$$Q_r = \frac{(\pi + 2\alpha)D^{1/2}}{(\pi + 2\alpha)D^{1/2} + (\pi - 2\alpha)} \quad (1)$$

Where $Q_r = q_L/q_0$, q_L and q_0 are the discharge per unit width of lower-layer and total flux, respectively. α is the entry angle near the slot. $D = \rho_a/\rho_L$, ρ_a and ρ_L are the density of the ambient water and the lower-layer flow, respectively.

In this study, all data were measured in each flume experiment when the outflow concentration and height of interface reached its stable situation. Thickness of high concentration stratified currents in this study was measured to complete the data in Yu et al. (2004). And the measured entry angles will be compared with the theoretical values calculated by the equation of Forbes and Hocking (1998).

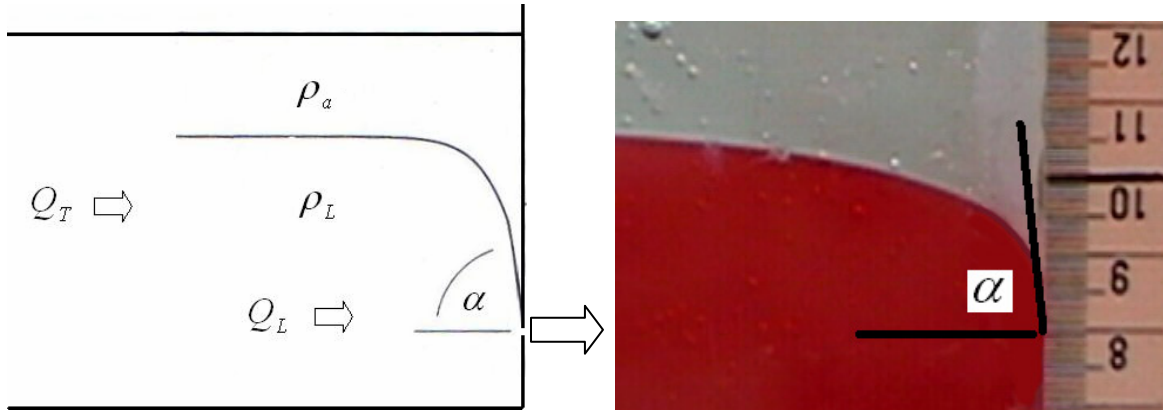


Fig. 3 An illustrative sketch of two-layer withdrawal condition

2. EXPERIMENTAL FACILITIES

The experimental design is based on the idea of generating a two-layered, density-different flow and withdrawing from a line sink (Fon, 2000 and Wang et al., 2004). The bottom slope of the flume is horizontal. The flume was divided into two channels, as shown in Fig. 4. The first channel was the test channel with a width of 5 cm and the adjacent 14 cm wide second channel was the clear water

channel. A 20 cm-long, 1cm-width indentation connected these two channels at the upstream end of the bulkhead.

There are two water supply systems in this laboratory setting; one for the saline water (the lower layer) and the other for the clear water (the upper layer). Clear water is added into the clear water channel and flow into the test channel via the 20cm indentation on the bulkhead. An indentation with an elevation of 39.5cm is used at the upstream end of the clear water channel for maintaining a water surface level of 40cm. So the surcharge clear water would be drained from the upper layer of the clear water channel and doesn't influence the flow condition of the test channel. The layout of the flume can be found in a work by Yu et al. (2004).

A slot was installed in the end wall of the test channel, which was the same with Gariel (1949), Harleman et al. (1958), Debler (1959), and Hocking (1991). The outflow discharge is controlled by the slot with a height of 0.25 cm and 5 cm wide. The elevation of slot was 8cm. Z_0 is the centerline elevation of the slot, so Z_0 equal to 8.125cm.

Using continuous settling of sediment particles within the muddy lake to reach a steady state is very difficult. Dissolved material like salt is used (as is done in most studies) to avoid particle settling. In addition, the dense part of the two-layer flow is constantly supplied to maintain a stable thickness of the lower layer, as was in previous studies see for example Ellison and Turner (1959), Ashida and Egashira (1975), Parker et al. (1987), Lee and Yu (1997).

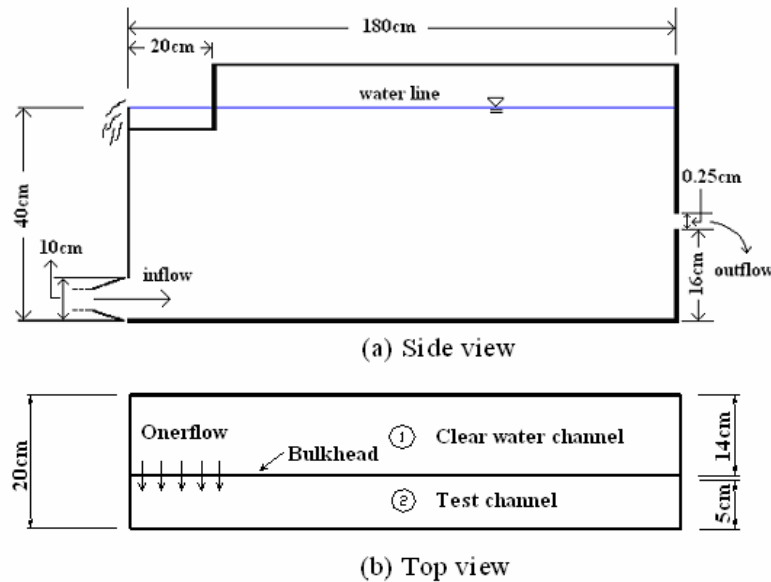


Fig.4 Layout of experimental set-up (a) side view (b) top view (Yu et al., 2004)

3. EXPERIMENTAL CONDITIONS AND PROCEDURES

The control parameters in the experiments are the concentration (C_{in}) and the discharge (q_{in}) of the inflow saline water. In this study, seven different inflow concentrations are used ranging from 11.2 to 229.5 gram per liter and eight different inflow discharges per unit width ranging from 0.997 to

12.07 liter per minute. The clear-water inflow rate, saline water inflow rate, and saline water inflow concentration are all kept unchanged during each experiment. Red dye is used to visualize flow condition of the interface which is between lower-layer flow and upper-layer flow of the two-layer flow. Experimental cases in this study are shown in Table 1.

Total water height in the test channel and clear water channel, H , are both kept at 40 cm. The relative height $Z_0/H \cong 0.2$, whereby Z_0 is the centerline elevation of the slot opening. The outflow concentration varied with time was measured. The thickness of the bottom stratified current and the vertical concentration profile on the representative section, 73.5 cm upstream from the end wall, are measured, until the equilibrium state is reached. A calibrated electrical conductivity probe is used to measure the concentration of the sampling saline water. The stable thickness of dense flow and the entry angle are measured and reported by visual interpretation and DV, respectively. The video reported by DV is used to double check the accuracy of the experimental data reported by visual interpretation. In general, the interface is not fixed, there will be about 5° variation around the average value of entry angles (Fig. 5).

Table 1 Experimental cases in this study

Concentration(g/L) Discharge (L/min)	11.17	17.17	23.55	30.26	59.26	113.84	229.52
0.997	●	●			●		
1.326	●	●			●		
2.13	●	●	●	●	●	●	●
4.31	●	●	●	●	●	●	●
6.40	●	●	●	●	●		
8.38	●	●	●	●	●	●	●
10.26	●	●	●	●	●		
12.04	●	●	●	●	●	●	●

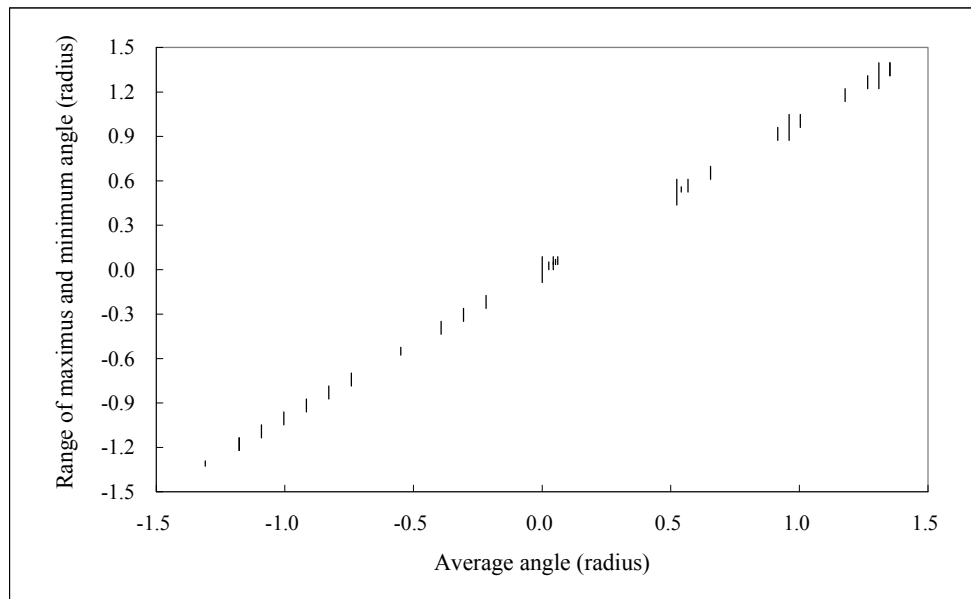


Fig. 5 Relation between variation range of entry angle and average angle

4. RESULTS AND DISCUSSION

4.1. Entrainment

Because of the fact that there is a mixing layer between the saline and ambient water it is impossible to identify a clearly defined interface between these two flows. Hence, in this study, the method of Buehler & Siegenthaler (1986) was adopted to determine the thickness, h , of the density current. Their method is as follows:

$$h = \frac{\int_0^{\delta} 2C' Z dZ}{\int_0^{\delta} C' dZ}$$

(2)

Where Z is the height measured upward from the flume bottom, C' is the concentration at elevation Z and δ is the elevation where the concentration approaches zero. There is no need to measure the velocity profile in order to apply Eq. (2). The calculated values of h were then compared with those visually obtained based on the dye shade. The layer-averaged concentration, C , was determined using:

$$C = \frac{\int_0^{\delta} C' dZ}{h}$$

(3)

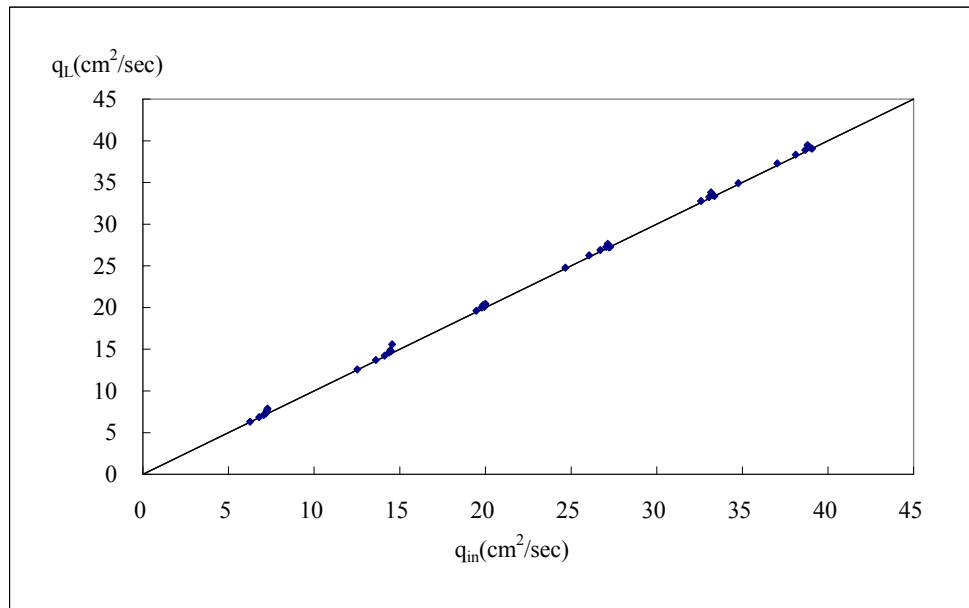
The discharge of the lower-layer flow could be calculated by the conservation of mass.

$$q_{in} \cdot C_{in} = q_L \cdot C_L \quad (4)$$

Where q_{in} is inflow discharge per unit width. C_{in} is concentration of inflow saline water. q_L

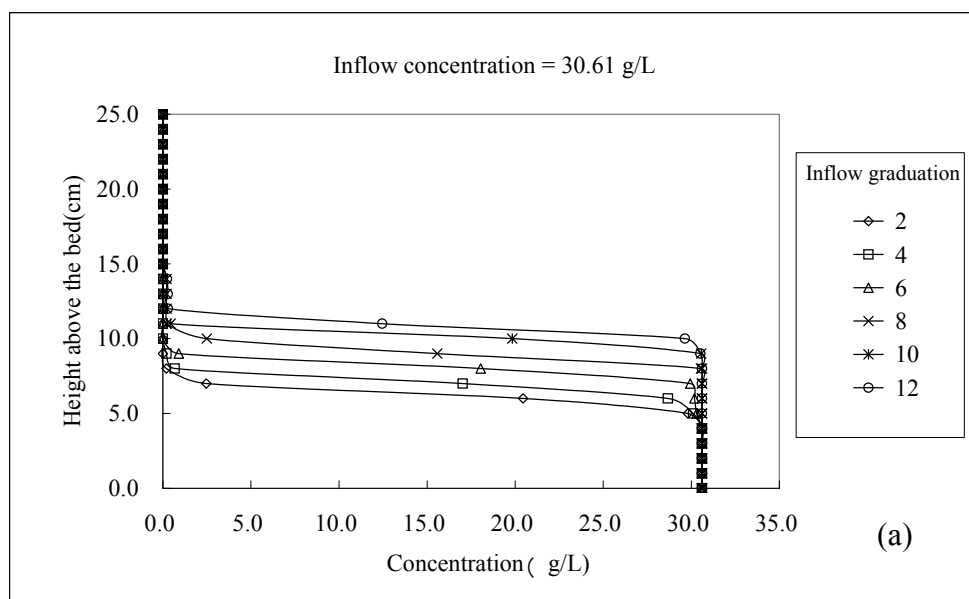
is average discharge per unit width of the lower-layer flow. C_L is layer-averaged concentration of lower-layer in the representative section.

From Fig. 6, $q_L \cong q_{in}$. It means that the entrainment, from the upper-layer to the lower-layer, is small and can be neglected in this study.



4.2. Concentration profile

Fig. 7 shows the concentration profile of the representative section. The variation of concentration is obvious on the mixing zone which is a transition between clear water and saline water. The concentration below the mixing zone is uniform and close to the concentration of inflow. The mixing zone will be thicker if the difference of the concentration between clear water and saline water is smaller. It means that if the concentration of the lower-layer flow is smaller, it will be easier to mix on the mixing zone and the mixing region will be wider.



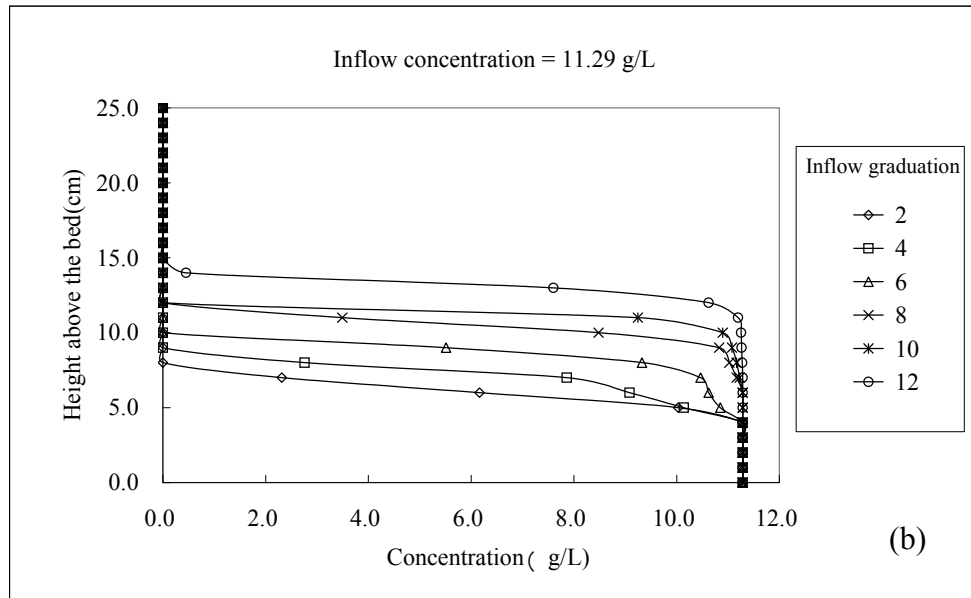


Fig. 7 Concentration profile on the representative section

4.3. Lower-layer thickness

From Fig. 8, it could be seen that the thickness will increase with the increasing of the inflow concentration when the interface is lower than the slot. On the other hand, it will decrease if the interface is higher than the slot. The variation of the thickness will become small and tend to a constant value when the inflow concentration keeps on increasing to a very high concentration (Fig. 8). With increasing inflow concentrations the thickness may decrease or even increase, however under no circumstances case will the thickness cross over the slot even if the inflow concentrations are increased to an extremely high value.

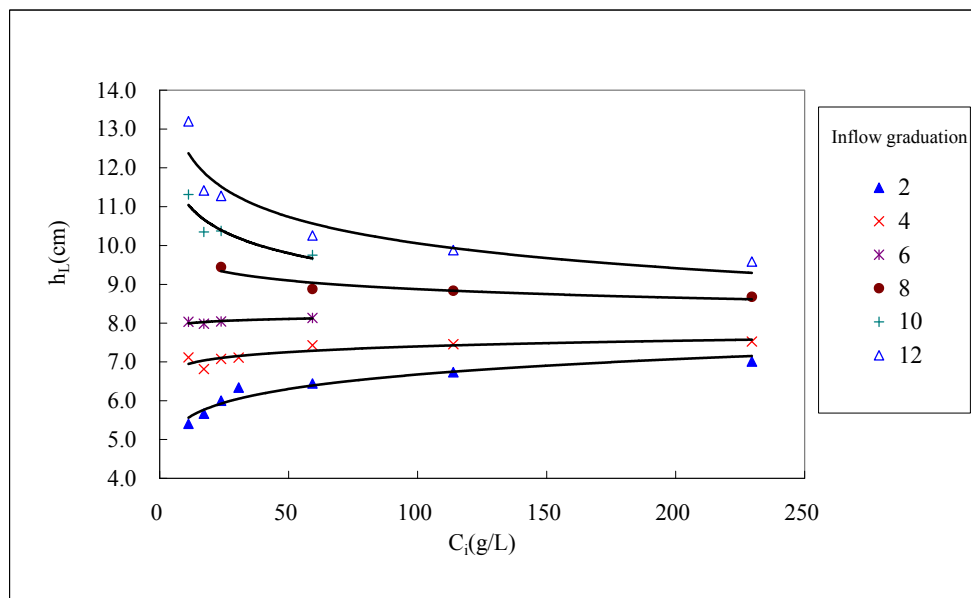


Fig. 8 Low-layer calculated equilibrium thickness and average concentration

4.4. Entry angle

When the interface is above the slot, the entry angle is positive; on the other hand, the angle is negative. Use Eq. (1) to calculate the theoretical angle. The relation between theoretical angle and measured angle was shown on Fig. 9. It could be seen that the measured angle theoretical angle is closer to the theoretical angle when the angle is small. The measured angles are underestimated from the theoretical angles when the angle is close to 90° . It might be that if the angle close to 90° , it will be difficult to measure very accurately because the interface is close to the end wall.

Fig. 10 is the relation between the discharge ratio (q_L/q_o) and the measured entry angle. When the discharge of the low-layer flow is bigger than the half discharge of outflow, the angle is positive. It means that the interface between the clear water and the saline water is above the slot. On the other hand, the angle is negative and the interface is under the slot. The relation between the discharge ratio and the measured angle is approximately linear when the angle is small. The blue line is regressed from the data in Fig. 10. It could be seen that when the entry angle is equal to 0° (the elevation of interface is equal to slot), the lower-layer discharge withdrew from the slot will be a little smaller than half discharge of total outflow discharge.

Fig. 11 is the relation between the thickness of the lower-layer flow (h_L) and the measured angle. It also could be seen that there is a better relation between h_L and the measured angle when the angle is close to 0° .

Our data agrees with the theoretical angle calculated by the equation of Forbes and Hocking (1998) which could be able to estimate the entry angle especially when the entry angle is small. The entry angle is a remarkable parameter, because it had good relation with the discharge ratio and the thickness of the lower-layer flow.

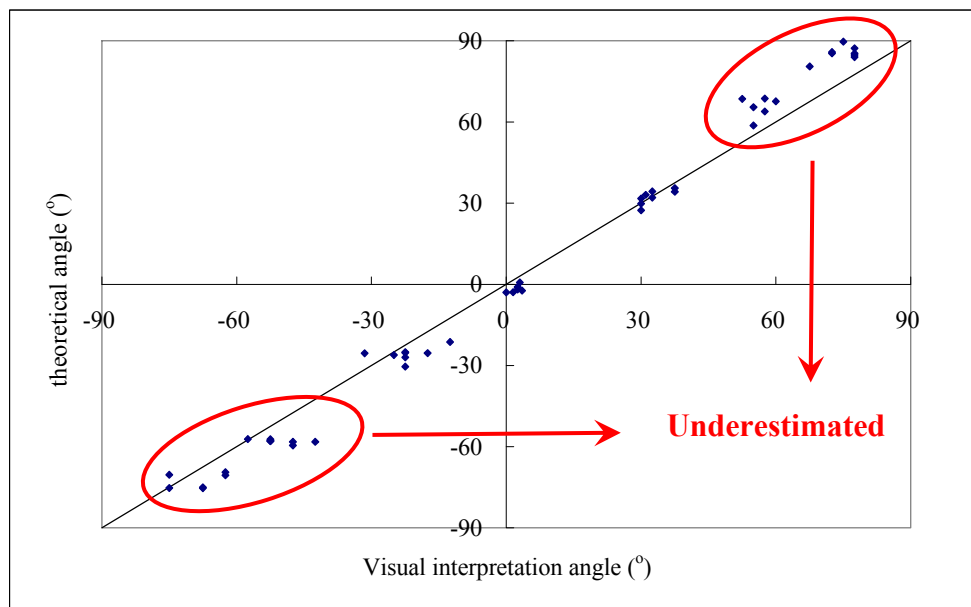


Fig. 9 The relation between theoretical angle and entry angle

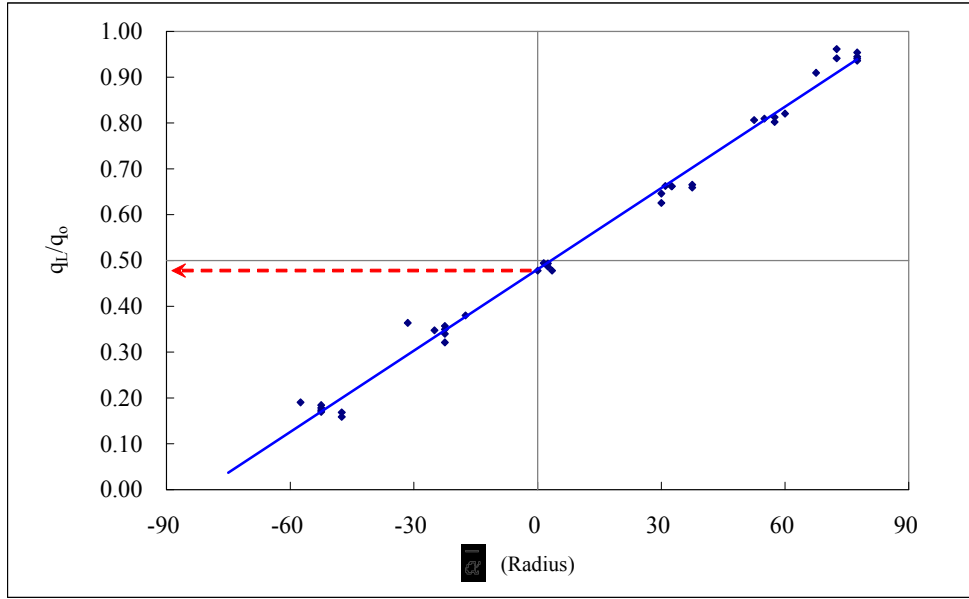


Fig. 10 The relation between q_L/q_0 and the entry angle

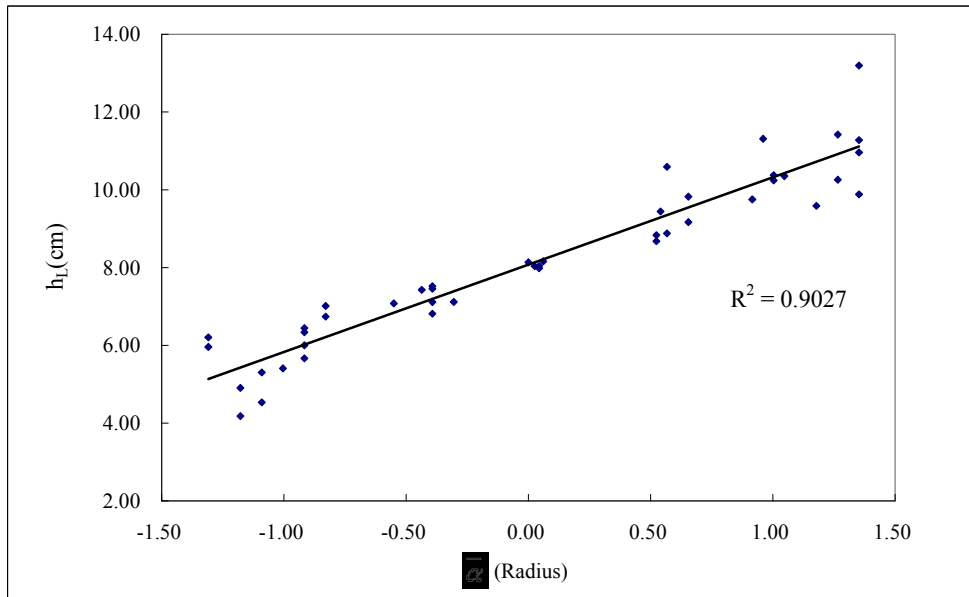


Fig. 11 The relation between h_L and the entry angle

5. CONCLUSIONS

The mixing zone will be thicker if the difference of the concentration between clear water and saline water is smaller. It means that if the concentration of the lower-layer flow is smaller, it will be easier to mix on the mixing zone. It could be seen that the turbulence on the mixing zone caused the same inflow discharge will cause more mixing if the density of the lower-layer flow is lighter.

If the inflow discharge is kept constant, with the increasing of the inflowing concentration the thickness will increase/decrease as the interface is lower/higher than the slot. The variation of the

thickness will become negligible when the inflow concentration increases to a very high concentration. Even the thickness will increase or decrease with the increasing of the inflow concentration, but it won't cross over the slot even the inflow concentration increasing to a very high concentration.

The relation between the discharge ratio (q_L/q_0) and the measured angle is approximately linear when the angle is small. When the entry angle is equal to 0° (the elevation of interface is equal to slot), the lower-layer discharge withdrew from the slot will be a little smaller than half discharge of total outflow discharge.

Our data agrees with the theoretical angle calculated by the equation of Forbes and Hocking (1998) which could be able to estimate the entry angle. The entry angle is a remarkable parameter, because it has good relation with the discharge ratio and the thickness of the lower-layer flow when the entry angle is small.

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